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The Long-Term soil productivity study after three decades

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1. Introduction

In 1989, the Long-Term Soil Productivity (LTSP) concept, and eventual study design, began with a conversation about the needs of forest managers in the USDA Forest Service to meet the requirements of the National Forest Management Act (NFMA) of 1976. This Act mandated that the productive capacity of forests be maintained on federally managed lands while also maintaining soil productivity. Soon after initiating the LTSP study within the USDA Forest Service, it was expanded to include partnerships with national and international researchers and managers to establish and maintain more than 100 LTSP and affiliated sites across North America (Fig. 1), as well as at several other international locations, including New Zealand, China, and Chile.

This collective set of installations now comprise the worlds' largest coordinated forest research network that addresses both basic and applied science issues of forest management and sustained productivity (Powers, 2006). Much of the history associated with the LTSP project, the definitions and standardized sampling protocols employed, and the core treatment experimental design is described in Powers (2006). In particular, four of the USDA Forest Service's Experimental Forests (Palustris, Challenge, Marcell, and Priest River Experimental Forests) played a pivotal role in piloting this work as described by Powers et al. (2014). Two soil key soil properties (organic matter and soil porosity) were selected as they are influential drivers that can change soil productive capacity since they govern many soil processes (e.g., nutrient availability, aeration, moisture retention) and regulate net primary productivity within a climatic and genetic framework (Fig. 2). In short, core sites have three levels of organic matter (OM) removal (bole only, whole tree harvesting, and whole tree + OM removed) and three levels of compaction (none, moderate, and severe). As additional treatments, many study sites had each 0.4 ha plot divided in half (split-plot) where herbicide was applied to one-half of the plot to eliminate competing vegetation allowing for an assessment of unimpeded crop tree growth vs. total vegetation growth. At affiliate sites, not all core treatments were applied and, in many cases, ameliorative treatments, such as fertilization or bedding, were used. However, the treatments represent a continuum of those commonly encountered after harvest operations and the relatively large plot size allowed for the soil conditions to be extended beyond normal operations to better describe the full extent of the effects that increases in OM removals and reductions in soil porosity may have on soil productivity, stand development, and crop tree growth potential across a wide range of forest types, soils, and macroclimates.

What does it take to sustain a long-term study from harvest through a full rotation across a wide range of forested ecosites? As highlighted by Powers (1999), the most important element is a sustained philosophical and administrative commitment by a nucleus of dedicated people who understand the benefits that can be gained through collaborative, long-term research. Active engagement from managers, scientists, and administrators is necessary to maintain these sites and to ensure continued, consistent measurement of common, core variables. The value of such a committed, collaborative effort lies in not only quantifying initial treatment responses, but, more importantly, describing the trajectories of ecosystem-level recovery. The initiation of this study network required partnerships between managers and scientists, commitments of land, investments in laboratories, training of graduate students, and engagement from politicians, practitioners, and the public, as well as

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coordination at a grand scale to accommodate replication of the core study design across such a wide range of site types. Another important element for sustaining this long-term network is that everyone involved has been and contuse to be bold! All participants in LTSP persist in efforts to seek funding, tell the story, and capitalize on opportunities to share the emerging science with a diversity of audiences through various outlets (e.g., field tours, workshop presentations, posters, pamphlets, technical reports, peer-reviewed publications). This study also endures because of its relevance to existing and emerging challenges related to the maintenance of healthy forests and soil, and clean water. The design and scale (i.e., large, replicated plots over a wide geographic range) ensure results are relevant to management and are scientifically robust. Camaraderie among network participants, including managers and researchers, has inspired the perseverance needed to overcome challenges faced with administrative processes.

What are our current challenges? One thing we've lost over three decades has been consistent financial support. Despite ongoing efforts to secure funds, the absence of a core financial commitment to this silviculture-soil study threatens its sustainability and rigor. Without the security of baseline funds, data collection has become less regimented and occurs when funds can be cobbled together. Another challenge is to continue or renew our commitment to multi-faceted and relevant science (Powers, 1999). Worldwide collaborators invested money, blood, sweat, and tears into the installations. We have forged collaborations to get re-measurements done. Today we are working toward developing operational limits for biomass removals in light of climate change, drought, increasing wildfire risk, and bioenergy opportunities. As the LTSP network and the associated, regenerating forests continue to mature, the results can (and will) be incorporated into forest policies and forest management guidance. For example, the LTSP study informed a USDA Forest Service-wide standardized forest soil monitoring protocol (Page-Dumroese et al., 2009). In addition, the Minnesota Biomass Harvesting Guidelines for Forestlands, Brushlands, and Open Lands relied on LTSP data to develop surface OM retention guidance (MFRC, 2007). As a Canadian (Ontario) example of forest management guideline changes supported by emerging LTSP results, whole-tree harvesting restrictions have recently been reduced (e.g., OMNRF, 2015) on both shallow-soiled sites and coarse-textured, infertile sands (Morris et al., 2020), formerly deemed sensitive to biomass removal levels associated with whole-tree harvesting. The maintenance and continued monitoring of Ontario's LTSP installations through to full rotation now represents part of an "effectiveness monitoring" requirement as part of the adaptive management cycle (i.e., guidelines are reviewed and revised, as required, on a 10-year cycle). As a further example, the emerging results from the LTSP collective provided the foundational science for Ontario's Biofibre Directive (https://www.ontario.ca/page/forest-biofibre-allocation-and-use), and related enabling policies, to support the development of Ontario's bioeconomy, that includes opportunities for community-based bioenergy projects (Puddister et al., 2011).

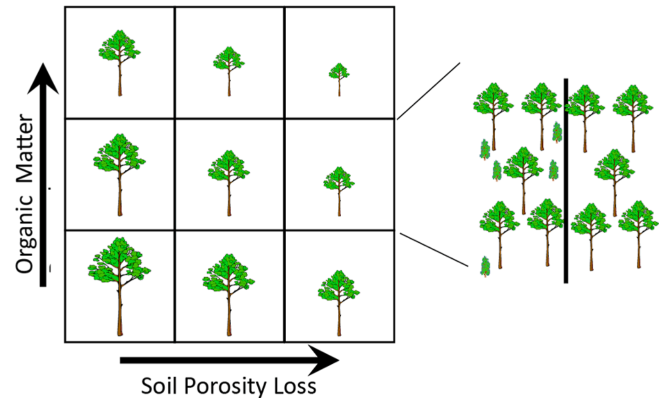

Fig. 2. Range of experimental units at core locations. Inset illustrates the herbicide and non-herbicide treatments. Plots are 0.4 ha in size.

As we progress through the 2020 decade and beyond, original (Fig. 3) and new collaborations are being leveraged and this group, individually and collectively through synthesis efforts such as this special issue, continues to produce and steward high-quality data about the effects that a pulse, stand replacing disturbance has on basic soil/site processes such as carbon (C) sequestration, vegetation growth, and above- and below-ground changes that drive productivity. In this special issue we asked authors to synthesize data (e.g., above- and belowground responses to the LTSP treatments applied) from multiple sites, with this

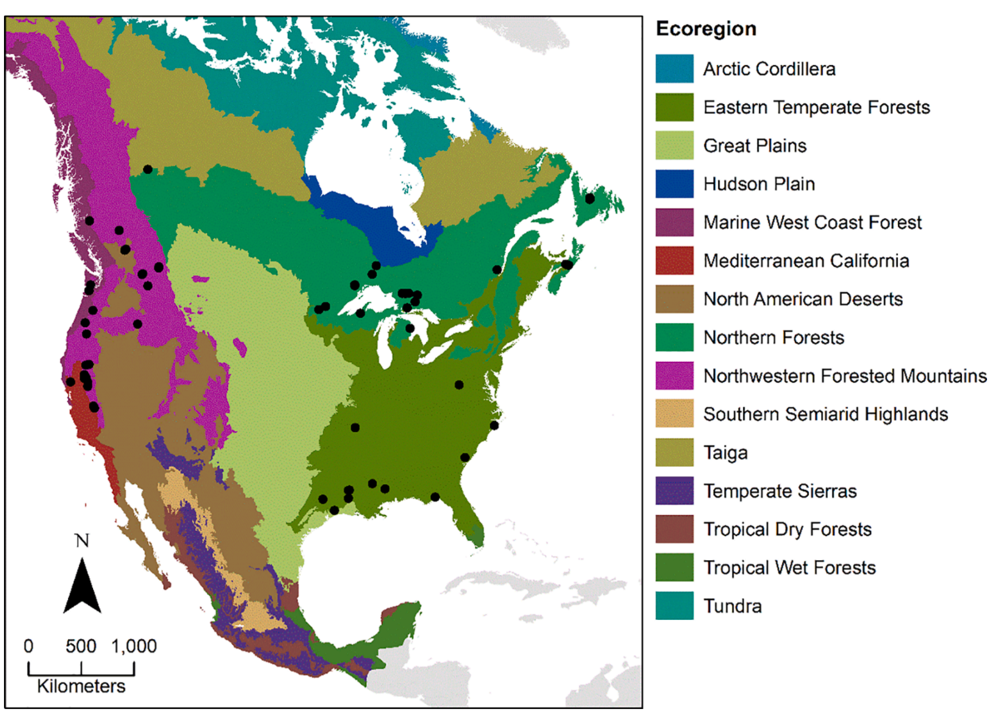

Fig. 1. Location of North American Long-Term Soil Productivity study sites.

Fig. 3. A few of the many collaborators that made LTSP possible: A. Bob Powers, the original developer and lead of the LTSP (photo by Mason Carter) B. 1995 meeting in British Columbia, C. 2004 meeting in Idaho, and D. 2012 meeting in Montana.

introductory paper describing just a few of the highlights with a focus on management needs (i.e., how does this science "enable" forest policy and inform both strategic and operational forest management decisions?). The collection of papers in this special issue illustrate how the research conducted across the LTSP network provides insights on how different site-specific factors, and their interactions mediate soil OM turnover, nutrient availability, microclimate (i.e., soil temperature and moisture), and competing vegetation that collectively drive forest dynamics and site productivity leading to plausible and defensible solutions for sustainable management of our forests.

2. Insights from past to present

2.1. Aboveground responses

As this study progresses, we are finding some early results persist through 25–30 years, while others have diminished, affirming the value of long-term research, and regularized, repeat measures of a core set of ecosystem attributes. For example, early summaries of many sites concluded that soil compaction, with the surface OM intact, usually benefitted planted conifer growth and survival regardless of climate or species (Fleming et al., 2006). Further, and as expected, vegetation control benefitted conifer tree growth across all treatments, most notably on the more productive (and more competitive) sites. Early results also indicated that soil texture was a key determinant of how sites responded to the LTSP treatments. In some cases, loam and clay soils responded negatively to compaction (Curzon et al., 2020), while sandy soils had the opposite response which was linked to still having adequate aeration along with improved moisture retention (Gomez et al., 2002). Results are showing that the impact of compaction and its role in reducing competing vegetation is still evident today and expressed in increased crop tree survival and growth (Zhang et al., 2017). One key message found in a number of the papers is that maintaining surface OM is critical on sites that are droughty and, as the climate changes, OM retention will become even more important for moderating soil temperature and retaining plant available moisture (Curzon et al., 2020; Kersey and Myrold, 2021). Over time, and as these regenerating stands reach crown closure on many LTSP sites, it is becoming apparent that sites low in nutrients benefit from the retention, turnover, and rebuilding of the surface OM (e.g., Wallace et al., 2021). This benefit can be directly linked to the loss of nutrients associated with OM and small-diameter residues, leaves, or needles removal on the whole tree harvest treatment. Results also highlight that monitoring crop tree performance alone may be an inadequate indicator of long-term soil nutrient sustainability (e.g., Garrett et al. 2021a).

2.2. Belowground responses

On many sites, compacted soils recovered rather quickly (Page-Dumroese et al., 2006), with coarse-textured soils (e.g., sandy, coarse loamy) recovering faster than those with finer textures (e.g., fine loamy and clayey). Although the surface mineral soil is recovering, soil compaction that extends deeper in the soil profile remains a concern at many locations (Busse et al., 2020). Similar to the aboveground responses, it was often the surface OM horizon loss that altered soil C and nitrogen (N) levels, and the amount of alteration (C and nutrient loss) was related to soil texture (i.e., coarse soils having greater relative losses than finer textured soils) (James et al., 2021). Although initial losses in soil C and nutrients occurred across all harvest treatments, both the bole only and whole-tree harvests, for the most part, showed similar declines and have signs of recovery out to 20 years. In contrast, the whole-tree harvest + OM removal showed much greater C and nutrient losses compared to the other two operational treatments and have not shown signs of recovery (Morris et al., 2019).

On many LTSP sites, microbial populations have either been sampled directly or indirectly (e.g., wood stakes as an index of OM turnover). In this regard, results from a number of sites showed that OM retention helped maintain soil moisture and moderates near-surface soil temperatures, that, in turn, helped to retain microbial community structures and functions (Wilhelm et al., 2017). However, beyond treatment effects, results also illustrate that local climatic regimes, in part, mediate microbial activity (Adams et al., 2021; Page-Dumroese et al., 2021).

3. Lessons learned

The papers in this special issue report the longer-term responses of forest sites to a pulse stand-replacing disturbance resulting in soil compaction and OM removal. A majority of the post-treatment developing stands are at crown closure and, as such, are likely exhibiting higher demands for soil nutrients and water (Fleming et al., 2021). These new papers highlight several results that land managers can apply to maintain long-term productivity and C storage:

- The long-term application of herbicide may not result in a continual increase in tree volume and therefore an evaluation of how long to apply herbicide treatments should be evaluated (Littke et al., 2020).
- The interaction of vegetation control and soil available nutrients needs further examination. Consideration of the tradeoffs of controlling aggressive competing species with preservation of plant available nutrients should be given (Littke et al., 2021).
- Maintenance of surface OM horizons at harvest is critical for long-term growth, C storage, nutrient retention and cycling, water conservation, and microbial functions. Given enough time, surface organic horizons will recover following disturbance (Garrett et al., 2021a; James et al., 2021)
- As these stands continue to develop, full-tree harvesting plus organic horizon removal has led to lower soil N availability than operational tree-length harvesting, and stands with understory vegetation control are now showing indications of reduced N availability (Hazlett et al., 2021)
- Deep soil compaction is still a concern out to at least 30 years, and this soil impact may not recover before stands are harvested again which could compound the existing negative effects on water retention, soil aeration, root growth, and microbial activity (Busse et al., 2020).
- In New Zealand, LTSP results underpin significant changes in management of forests for supporting microbial health and soil nutrition and soil sampling depth has been increased to recognize the importance of evaluating deep (1 m) soil C and nutrients (Garrett et al., 2021b).
- Placing post-harvest response in the context of relationships among stand development, changes in microclimate that mediate soil processes, and resource supply and demand should provide greater insights into longer-term effects of harvest and establishment practices (Fleming et al., 2021).
- On coarse-textured, low-productivity soils, organic matter removal and compaction treatments had relatively few negative effects on tree height, which indicates resilience of oak and pine species in the Ozark Highlands (Lyczak et al., 2021).
- Forest harvesting, woody residue dispersal or piling, vegetation control, and regeneration practices can influence vegetation recruitment and competitive relationships which can limit longer-term forest productivity (Harrington et al., 2020)

At 20–30 years old, our collaboration of motivated individuals has proven that this grassroots effort has created a major network that provides key scientific data to relevant to land managers and policy makers. Our network highlights the need to develop and use best management practices that avoid soil disturbances rather than trying to mitigate impacts. For soil compaction, we found that dispersed rather than concentrated forwarding patterns, use of slash mats on trails or near landings reduces deep compaction, or that harvesting finer-textured soils while the soil is frozen can reduce the negative change (decline) in soil aeration and porosity and allow for greater infiltration. From an OM retention perspective, the LTSP network has generally found that bole only and whole tree harvesting do not tend to result in lasting negative effects, but there are some regional and site-specific differences that support the need for 'customized' approaches in different geographic areas. In contrast, whole tree harvesting with surface OM removal had significant and lasting negative effects which may tip the scale in terms of ecosystem stability. This suggests that there is a threshold level of OM retention that likely lies somewhere along the continuum of treatments and urges a cautionary approach to adopting higher biomass utilization systems that support the bioeconomy. These results still call for ongoing measurement of the installations with particular emphasis on determining when soil properties return to pre-treatment levels, how the pulse disturbances effect total biomass yield at the end of the rotation, and how forest management treatments might alter soil C within a changing climate.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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